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SPACE STATION TELEROBOTICS: DESIGNING A HUMAN-ROBOT INTERFACE

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The experiments described in this paper are part of a larger joint MIT/NASA research effort and *focus on the development of a methodology for designing and evaluating integrated interfaces for highly dexterous and multi-functional telerobots. Specifically, a telerobotic workstation is being designed for an Extravehicular Activity (EVA) anthropomorphic space station telerobot called Robonaut. Previous researchers have designed telerobotic workstations based upon performance of discrete subsets of tasks (for example, peg-in-hole, tracking, etc.) without regard for transitions that operators go through between tasks performed sequentially in the context of larger integrated tasks. The experiments presented here took an integrated approach to describing teleoperator performance and assessed how subjects operating a full-immersion telerobot perform during fine position and gross position tasks. In addition, A Robonaut simulation was also developed as part of this research effort, and experimentally tested against Robonaut itself to determine its utility. Results show that subject performance of teleoperated tasks using both Robonaut and the simulation are virtually identical, with no significant difference between the two. These results indicate that the simulation can be utilized as both a Robonaut training tool, and as a powerful design platform for telepresence displays and aids.

INTRODUCTION

Research is currently being conducted to design and test an intuitive and synthesized telerobotic workstation configuration for controlling a high degree of freedom dexterous manipulator for use on the International Space Station. The construction and maintenance of the International Space Station is expected to increase the number of Extravehicular Activity (EVA) hours by a factor of four over current Space Shuttle missions, resulting in higher demands on the EVA crewmembers and EVA crew systems. One approach to utilizing EVA resources more effectively while increasing crew safety and efficiency is to perform routine and high-risk EVA tasks telerobotically. In response, NASA's Johnson Space Center (JSC) is developing an anthropomorphic telerobot called Robonaut (see Figures 1,2) that is capable of performing all of the tasks required of an EVA suited crewmember.

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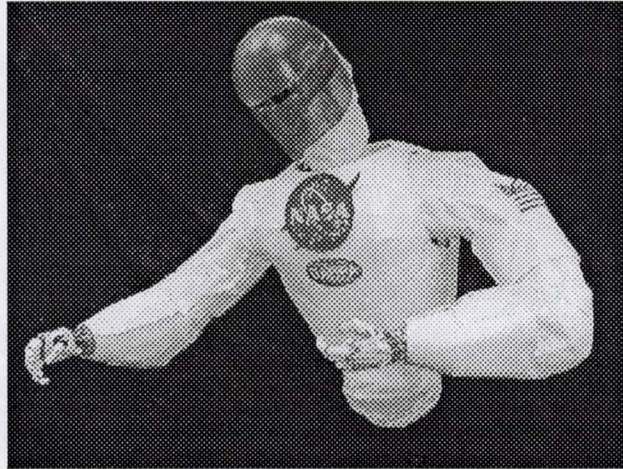


Figure 1. Robonaut (in development).

Robonaut is comparable in size to a suited crewmember and requires the operator to command over 46 degrees of freedom while performing full immersion telerobotic tasks. The desire to develop a methodology for designing integrated workstations is motivated by next-generation robots such as Robonaut. The current robotic workstation for the Space Station robots consists of flat panel displays and 6 DOF hand controllers. This is insufficient for controlling highly dexterous anthropomorphic manipulators such as Robonaut. The workstation must be designed to allow an operator to intuitively control numerous degrees of freedom simultaneously, in varying levels of supervisory control, for all types of EVA tasks.

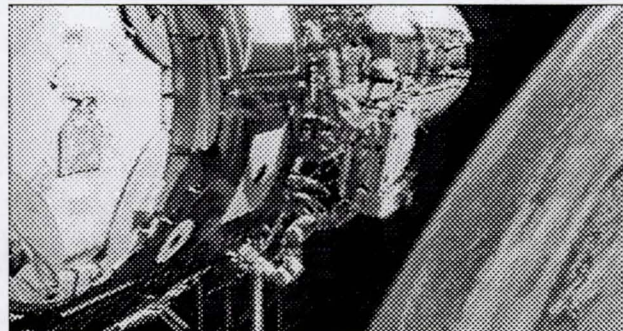


Figure 2. Graphic of Robonaut performing an ISS EVA task

Great amounts of research have been conducted in human factors areas such as telerobotic interfaces, human-machine interactions, and sensory substitution. However, many of the tasks performed in the experiments described in the literature do not capture the variety and complexity of the tasks required of an EVA crewmember. In most studies, optimal workstation components are determined based on performance of discretized subtasks (such as peg-in-hole, tracking, target acquisition, etc.) without regard to the transitions that the operator must go through between tasks performed sequentially (Burdea, 1996; Cannon and Thomas, 1997; Massimino, 1992; Sheridan, 1994). In addition, much of the research focuses on a particular hardware or software aspect of the workstation without addressing the synthesis of components required to tackle the human factors and controls issues of the system as a whole (Kazerooni and Snyder, 1995; Liu and Tharp, 1993; Massimino, 1988; Patrick, 1990; Shattuck, 1994; Sheridan, 1993; Vidov, 1993). Finally, the few groups that have looked at workstations as a whole either have not had to control as many degrees-of-freedom as Robonaut demands, or have controlled high degree-of-freedom robots that lack the dexterity of Robonaut, and therefore employ hand controllers (Akin, 1986; Homan and Gott, 1996; Li and Cox, 1995; Sheridan, 1992; Tachi, 1991).

A concern when designing workstations for robots such as Robonaut is what method should be used for development of new interfaces, displays and aids. It is safer and more effective to refine such situation awareness displays and aids before applying them to the Robonaut hardware, however one must ensure that the methods used to develop them are transferable to the actual robot hardware. Finally, the question arises of how to train operators

to use the robot. It is desirable to create a library of knowledge and experience for any new operator before allowing them to command the robot hardware directly.

A series of experiments has been devised and conducted at JSC to characterize the effects of telepresence hardware, sensory feedback degradation and task integration on full-immersion telerobotic task performance and workstation design. In addition, a Robonaut simulation has been developed and evaluated for use as a potentially powerful situation awareness development and operator training tool. One hypothesis tested is that subject teleoperation task performance using the simulation is comparable to Robonaut teleoperation performance, and therefore the simulation can be utilized as a telepresence interface development and operator training platform.

ROBONAUT TELEOPERATION

A Robonaut teleoperator wears a variety of virtual reality display and control technology to immerse them in the robot's workspace, thereby creating a sense of 'presence' at the robot worksite. The user's body position, tracked by an array of sensors, is sent as a command to the robot software that in turn generates the robot motions. For the Robonaut system, the teleoperator is seated in a remote location wearing instrumented Virtual Technologies, Inc. (Palo Alto, CA) Cyber Gloves that measure the displacement and bending of the fingers. A Polhemus FASTRAK® (Colchester, VT) system measures the position of the subject's hands, head, arms and head relative to a fixed transmitter. For these experiments, only the right hand/arm, chest and head sensor is utilized.

Robonaut has two cameras for eyes and the live video feed received from them is sent to a Kaiser Electro Optics, Inc. (Carlsbad, CA) ProView 60 helmet-mounted display (HMD) such that the human sees through the HMD what the robot sees. A transmitter is also mounted on the helmet so that the motions of the user's head are tracked. As the operator moves his/her head to the right or left, the robot likewise turns its head. In this way, the human is meant to feel that they are immersed and present at the robot site doing the tasks themselves. Figure 3 shows a subject seated wearing the telepresence hardware.



Figure 3 Subject wearing telepresence hardware including HMD, CyberGlove, and Polhemus trackers

ROBOSIM

Robosim (See Figure 4) is under development at the JSC Dexterous Robotics Laboratory. It uses the Interactive Graphics, Operations and Analysis laboratory (IGOAL) Enigma modeling software (Houston, TX) to create the robot models, environment conditions and camera view, and Real Time Innovations, Inc. (RTI) Network Data Delivery Service (NDDS) software for developing the necessary communication networks and protocols.

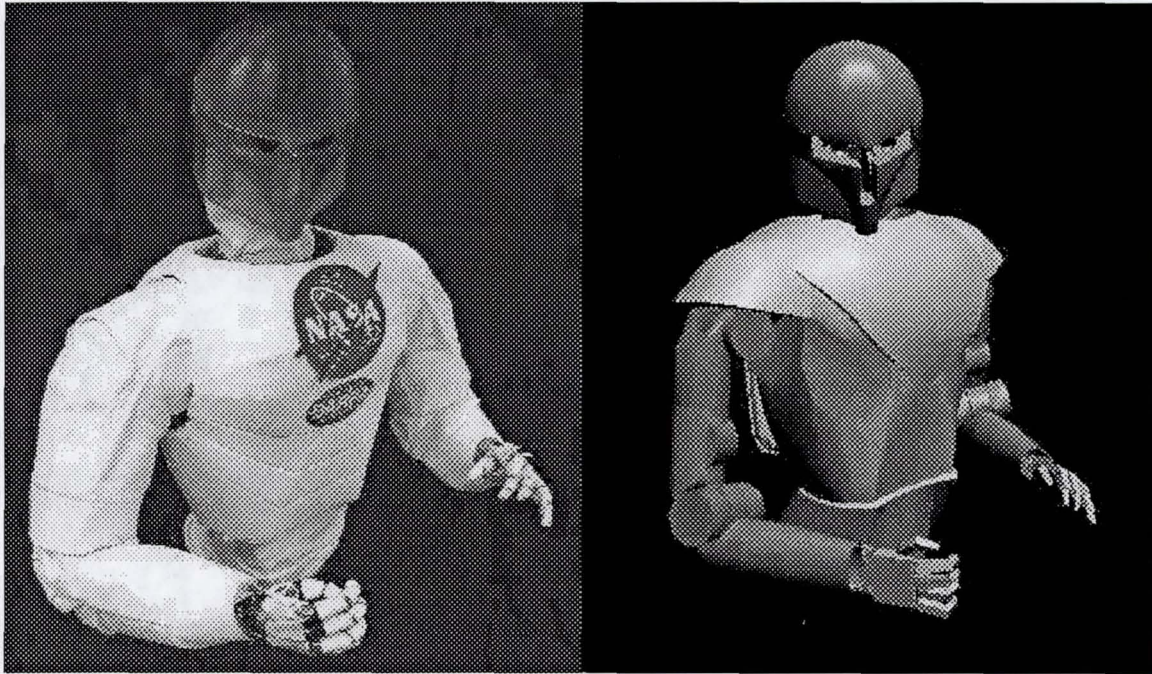


Figure 4 Robonaut and Robosim graphic

Robosim employs the identical forward and inverse kinematics as the Robonaut brainstem, therefore given the same command signal, the resultant motion of the simulated robot will match that of the Robonaut. Currently, the simulation is limited in that it does not model contact forces, therefore is not possible to study grasping and tool handling tasks.

Two Dell Latitude C600 laptops generate the 3-D Robosim views of the robot arms and task panels. Recall that Robonaut has two cameras, one for each eye, which together provide stereo vision to the operator. To generate stereo vision with an HMD using Robosim, it is necessary to generate two different graphical views of the same scene, separated by the same interocular spacing as the Robonaut cameras. Note that the HMD view generated through the simulation has the identical 60 degree diagonal field of view as the Robonaut cameras. Figure 5 shows the view from one eye that the subject sees in the HMD.

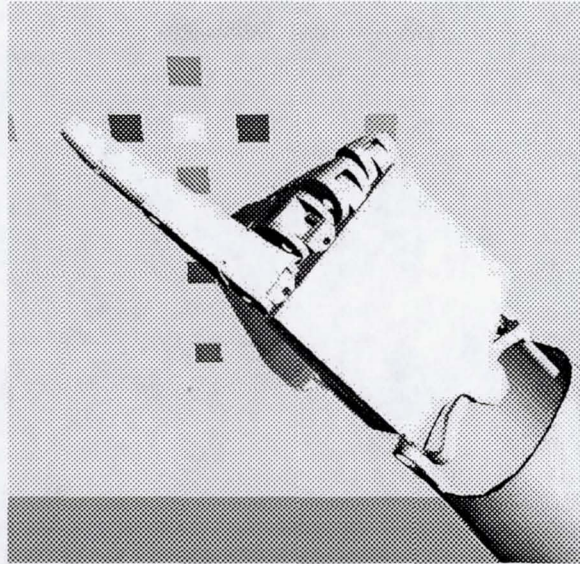


Figure 5 View of right eye through HMD of Robosim

EXPERIMENTAL METHODS

A protocol has been developed which tests task time, workload (both objective and subjective) and accuracy for gross position, and fine position tasks performed individually. The tasks span the workspace of the robot arm in all directions. Examples include swinging the arm through a large range of motion from an initial to final position, and fine positioning of the arm utilizing single joints or multiple joints in different orientations. This work was based in part, on teleoperation experiments previously conducted by the author. It was shown that up to thirty percent of the total task time was spent gaining better situation awareness (SA) (scanning the worksite between movements or tasks for a greater sense of the workspace layout and their position within it, and to decide how best to perform the next task) and the average across all operators and days was 10%. This work revealed two important observations, 1) as operator experience with teleoperation increases the time spent gaining SA information does not decrease without bound, there exists a baseline amount of SA time required for a given task and workstation configuration; 2) this baseline amount of SA time may be reduced by designing appropriate workstation interface aids. The current experimental methodology has been designed to both a) isolate the effects of interest and b) minimize the effect of confounding variables. This study is likewise designed to not only describe teleoperator performance using Robonaut, but to evaluate the newly developed simulation.

Basis Task Testing

The basis tasks were devised in order to describe teleoperator behavior during fine position and gross position tasks. They were so named after an initial study revealed that all astronaut motions during an EVA operation could be categorized as movements of gross position, fine position, grasping or combination of the three. In addition, the basis tasks are designed for simplicity and do not require force sensing or force feedback (although could be augmented with such). The basis tasks can be completed and compared across a variety of modalities, including zero-G, and performed using almost any teleoperated robots or robotic manipulator.

The basis tasks are comprised of two task panels (see Figure 6), one similar to a FITT tapping task, and the other containing a tracing pattern. While each panel combines elements of both fine and gross position movements, the tapping task is primarily a fine position task while the tracing task examines gross position movements.

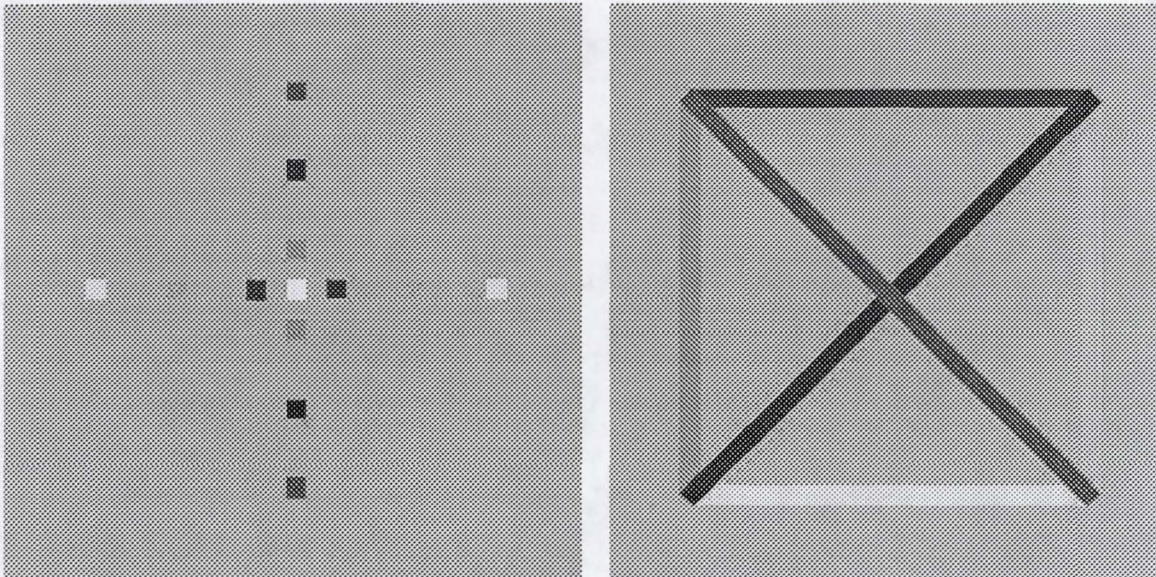


Figure 6 Basis task panels

On the tapping panel, subjects will be instructed to tap between like colors with their index finger. The size of each target is one-half inch square (the approximate width of the Robonaut index fingertip) and they are arranged in both the horizontal and vertical directions. The white target in the center is the starting point for each trial. The red and green targets are one inch from center, orange and blue are three inches from center, and yellow and purple are five inches from center.

The tracing panel involves following a path around the square and through the diagonals with the index finger. The clockwise path traces the red-orange-yellow-green-blue (top right to bottom left)-purple (top left to bottom right) path, and the counterclockwise path begins with purple (bottom right to top left) and goes in the reverse order. The blue and purple lines were oriented such that subject must reposition their hand and arm before tracing those lines. Each line is ten inches long and one-half inch wide. The area of the tracing square and the maximum distance from the center to the yellow and purple targets was chosen to comply with the reach envelope of the right arm of the Robonaut.

As is mentioned in the previous chapter, the Robonaut simulation was created with future Robonaut training in mind. To this end, it was desired to test if the simulation performance could match the robot performance as it was tasked to do. As these are the first set of experiments conducted using the simulation, its ability to match Robonaut's performance had not been quantified.

The basis tasks were tested in three modes. First, in order to describe the baseline performance for each subject and identify their particular subject effects, the basis tasks will be performed manually. In addition, the basis tasks will also be performed using a Robonaut simulation and telerobotically, where the subjects command the robot to do the grasping, fine position and gross position tasks.

- Manually with HMD

To isolate the effect on basis task performance of the vision system hardware, the protocol will be performed manually with the addition of the HMD. This will reveal the effect of degraded field of view and depth perception.

- Telerobotically with Simulation

Subjects will perform the basis tasks by teleoperating a simulation of Robonaut. The computer generated Robonaut will be commanded by the subject and the view from the simulated Robonaut eyes will be displayed to the subject through a helmet-mounted display. These tests will act as a training buffer between the manual and the telerobotic tasks, as the simulation possesses the same kinematics as the robot and therefore subject will gain practice with the kinematics before controlling the robot directly.

- Fully Immersed

To quantify any coupled effects between the vision system and the proprioceptive system, the basis tasks will be tested while the subject is fully immersed. They will again wear an HMD displaying the view from the Robonaut camera eyes.

Note that ensuring that the subject wears an HMD for each modality removes the vision system as a parameter in the teleoperation description.

A total of eight subjects (four male and four female) participated in the experiment. None of the subjects had prior experience teleoperating Robonaut. For this reason, one hand-one arm tasks were chosen to minimize the number of degrees of freedom and therefore complexity of the teleoperation task. This also allowed for greater control over Robonaut safety during the trials. All tasks were conducted using the right hand and only right-handed subjects are used.

For each modality (manual, simulated and robotic), a session consisted of 32 trials. There are six colored pairs of tapping targets and two tracing directions (clockwise and counterclockwise). Each is performed four times in a balanced order. Each trial is 25 seconds in duration. Training sessions were conducted for each modality. Subjects were introduced to the specific modality and given the task instructions. For the manual tasks, subjects are instructed to tap between like color pairs, or trace the pattern continually until time is called. For the simulated tasks, subjects are instructed to do the same however are told additionally not to penetrate the virtual task board with either their index finger or their hand (as contact forces are not modeled, subjects may drive the virtual robot hand through the plane of the virtual task board). Likewise for the robot trials, subjects are instructed not to "punch" the board or drag the robot finger along the board. For the latter two experiments, there was no force feedback to the operator as to whether contact was made, however subjects could visually observe if any part of the hand went through the virtual task board, and the deflection of the task panel if the robot was in contact with it. Following the trials, a subjective questionnaire is administered to the subjects.

RESULTS AND DISCUSSION

Table 1 summarizes the repeated measures analysis effects of modality, color (distance from center), location (vertical or Horizontal), and gender on number of taps, number of errors. As expected, the number of taps and traces completed during the manual trials was greater than with the simulation or robot, however across virtually effect, there is no significant difference between telerobotic and simulated telerobotic task performance. All color tapping and tracing were similar with the exception of red taps where subjects averaged three more taps than telerobotically, enough to make a significant difference ($P=0.009$). Other areas that did show significance were gender effects. Men had significantly more taps than women for the robotic tasks in all tasks except the clockwise trace, however they also had significantly more errors than the female subjects overall ($P=0.002$). There was no statistical difference between horizontal and vertical directions in either number of taps or number of errors. However there were significantly more traces in the clockwise direction than in the counter-clockwise direction.

In conclusion, these experiments have demonstrated that Robonaut telerobotic performance can be equally achieved using Robosim and therefore Robosim can be used in the future to develop Robonaut workstation situation awareness aids, as well as to develop operator training skills.

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